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EXPERIMENTAL RESEARCH REINFORCED CONCRETE BEAMS WITH THROUGH HOLES IN TORSION

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ABSTRACT

The relevance of the work is due to the need to obtain experimental data during the torsion test of reinforced concrete beams with through holes, as well as the development of methods for assessing their bearing capacity.

This article is devoted to the study of these issues, the solution of which has important theoretical and practical significance:

- ***The results of experimental and theoretical studies of strength, elements of a rectangular cross-section with through-holes during torsion;***
- ***Data on the effect of holes of various sizes on the strength of through beams;***
- ***An updated method for calculating the strength of reinforced concrete beams with through holes for torsion.***

The developed method for calculating the strength of reinforced concrete rods in the presence of torsion is based on their actual work. The reliability of the proposed recommendations for the calculation and design of rectangular beams with through-holes during torsion is based on the experiment of the authors.

KEYWORDS: Concrete, Reinforcement, Reinforced Concrete, Beam, Torsion & Strength

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Original Article

1. INTRODUCTION

In the foreseeable future, reinforced concrete will remain the main material in the practice of modern construction. Therefore, reducing material consumption and increasing the reliability of reinforced concrete in a market economy are prerequsites for the design and operation of buildings and structures.

One of the ways to ensure this is through the development of calculation methods that correspond in the best way to the actual work of structures that allow us to lay a reasonable margin of safety in the design of reinforced concrete elements.

The complexity of the task of developing methods for calculating the strength of reinforced concrete during torsion is due to the variety of cases of failure. In turn, the nature of the fracture depends on the shape of the cross-section, the transverse and longitudinal reinforcement patterns, the ratio of the power intensities of the longitudinal and transverse reinforcement, as well as the ratio of the compressive strength of concrete and the tensile strength of reinforcing steel. Such a variety of fracture cases and the parameters on which these cases depend, when they are studied, suggests the need to attract experimental material.

2. MODALITY

There are several proposals for assessing the strength of reinforced concrete rods in torsion. At the same time, some researchers are based on their calculation models, while others are trying to improve these models. The first publications [13, 14, 15] are devoted to the study of the strength of reinforced concrete rods during torsion appeared in Germany at the beginning of the 20th century.

The scheme of the distribution of forces in concrete and reinforcement proposed by E. Mersh [15] has received universal recognition, and is still being refined and modernized. The theory of E. Mersch is one of the directions in the study of the strength of reinforced concrete during torsion.

The strength of reinforced concrete elements under torsion and bending with torsion has been studied by V. N. Baikov and A. V. Belubekyan, E. G. Elagina, A. A. Gvozdeva, A. S. Zalesov, D. Kh. Kasaev, N. I. Karpenko, A. M. Kuzmenko, N. N. Lessig, G. V. Murashkina, H. M. Nadzhafova, G. S. Oganjanyan, O. N. Pechenik, R. A. Skladneva, N. I. Timofeeva, L. V. Faleeva, V. I. Fomicheva, T. P. Chistova, V. N. Yudin, N. N. Yachmeneva and others. Abroad - the works of A. Bishar, D. Victor, R. H. Gangarao, G. Gezund, K. Iengar, P. Zia, D. Kirk, D. Klus, G. D. Cowen, A. Macmillan, P. Mukherji, T. Hsu, Evans, etc.

Various studies with the most interesting approaches in solving the problem are considered. These experimental studies of reinforced concrete elements of rectangular continuous cross-section, with through holes and slit during torsion, and determine the effect of holes of various sizes on the strength of beams.

2.1 Design Solutions Prototypes

The experimental beams were adopted in a rectangular section with through holes of 150x220 or 150x270 mm in size and 2000 mm long. Beams differed from each other by the length and height of the hole. The design dimensions of the cross section of the branches of the beams are assumed to be the same for all samples and are 110x150 mm. As longitudinal reinforcement in prototypes, class AIII rods with a diameter of 12 mm were adopted, which were located at the corners of the cross-section of the branches of the experimental beams. Cross reinforcement in the form of closed clamps is adopted from class AI fittings with a diameter of 6 mm.

Seven prototypes were manufactured. One beam was a continuous rectangular section with dimensions of 150x220 mm. The remaining 6 beams are with holes and a gap.

The first group of the series consisted of three beams with branch cross-sectional dimensions of 110x150 mm and a horizontal hole in the middle of the prototypes equal to 5 mm (BT 30-0, BT 60-0, BT 90-0). The total cross-sectional dimensions of the prototypes, taking into account the size of the holes, were 150x220 mm.

The second group of the series consisted of three beams with the cross-sectional dimensions of the branches 110x150 mm and the horizontal hole height in the middle of the prototypes equal to 50 mm (BT 30-5, BT 60-5, BT 90-5). The total dimensions of the cross section of the beams, taking into account the size of the holes, were 150x 270 mm. The length of the hole of the beams within the same group was 300, 600 and 900 mm.

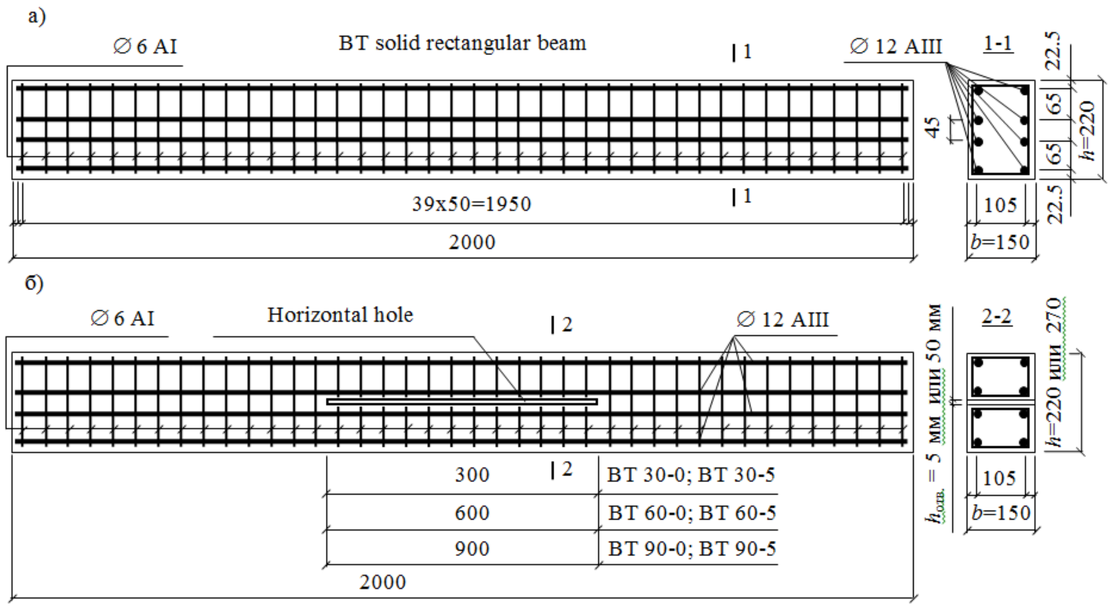

Figure 1: Design and Dimensions of Prototypes. a) Control Sample of a Solid Rectangular Section; b) - Samples of Rectangular Cross-Section with Horizontal Holes 5 mm High (Group 1 - Beams BT 30-0; BT 60-0; BT 90-0) or 50 mm (Group 2 - Beams BT 30-5; BT 60- 5; BT 90-5)

All beams of the series were tested for pure torsion.

The main characteristics of the experimental beams are shown in table 1.

Table 1: The Main Characteristics of the Prototypes

№ п/п	Cipher samples	Dimensions Cross section (cm)					Dimensions holes (mm)		Fittings			
		b	h	b_s	h_s	b_o	мм	Height (width)	Longitudinal		Transverse	
									∅ (mm)	A_s (cm^2)	∅ (mm)	A_{sw} (cm^2)
1.	BT	15,0	22,0	10,5	17,5	12,75	-	-	12	1,13	6	0,285
2.	BT 30-0	14,8	22,0	10,4	17,5	12,55	300	5	12	1,13	6	0,285
3.	BT 60-0	15,0	21,8	10,6	17,3	12,75	600	5	12	1,13	6	0,285
4.	BT 90-0	15,1	21,9	10,7	17,4	12,85	900	5	12	1,13	6	0,285
5.	BT 30-5	14,9	27,0	10,5	22,5	12,65	300	50	12	1,13	6	0,285
6.	BT 60-5	14,9	26,9	10,5	22,4	12,65	600	50	12	1,13	6	0,285
7.	BT 90-5	15,0	26,9	10,6	22,4	12,75	900	50	12	1,13	6	0,285

The alphanumeric codes in the codes of the prototypes mean the following:

BT - prototypes tested for pure torsion;

The first digits of the code 30, 60 and 90 are the length of the horizontal or vertical hole (cm);

The second digits of cipher 0 or 5 - hole height (cm);

The third digit of the cipher - determines the value of the ratio between the twisting and bending moments.

2.2 Mechanical Characteristics of Materials

To determine the strength and deformation characteristics of the reinforcement, samples were tested for short-term tension by the requirements of GOST [3, 4]. The samples consisted of □ 6 mm class AI reinforcing bars and □ 12 mm of class AIII.

Table 2: The Basic Geometric and Strength Characteristics of Steel-Grades AI and AIII

№ образца	Диаметр (mm) and class reinforcement	Condition arr. by the time of the test	Weight of sample (g)	Sample Length (mm)	Cross-sectional area of the sample (cm2)	Base measurement, l_o (mm)	l_k (mm) after the break	Module resilience (MPa)		σ_y (MPa)			σ_u (MPa)			δ (%)	
								E_s^{exp}	$\overline{E}_s^{exp}$	Experience	$\overline{\sigma}_y^{exp}$	GOST [10]	Experience	$\overline{\sigma}_u^{exp}$	GOST [10]	Experience	GOST [10]
1.	Ø 6 AI	Source	89,8	400,1	0,286	100	125,0	209000	210330	292,4	326,2	235	386,6	399,3	380	25,0	25
2.			89,6	400,4	0,285	100	123,4	208000		313,5		235	398,5		380	23,4	25
3.			89,2	400,2	0,284	100	124,2	207000		313,5		235	398,5		380	24,2	25
4.			90,5	400,3	0,288	100	123,8	215000		392,2		235	410,6		380	23,8	25
5.			88,9	400,2	0,283	100	124,5	211000		320,1		235	399,8		380	24,5	25
6.			89,2	400,1	0,284	100	124,1	212000		325,6		235	401,6		380	24,1	25
1.	Ø 12 AIII	Source	443,0	500,3	1,128	160	177,5	205000	199660	566,0	560	390	697,0	672,5	600	10,9	14
2.			444,9	500,2	1,133	160	179,8	197000		558,0		390	658,0		600	12,4	14
3.			442,4	500,1	1,127	160	179,2	195000		558,0		390	652,0		600	12,0	14
4.			444,3	500,0	1,132	160	178,5	196000		558,0		390	652,0		600	11,6	14
5.			442,1	500,2	1,126	160	178,2	202000		560,0		390	688,0		600	11,4	14
6.			445,2	500,1	1,134	160	178,6	203000		560,0		390	688,0		600	11,6	14

Notes: lk is the length of the sample after a rupture based on the measurement (mm); elongation, which was determined by the formula $\delta = [(lk - lo) / lo] \cdot 100\%$.

The strength characteristics of concrete were determined by testing standard concrete cubes with a rib size of 15 cm in strict accordance with the requirements of GOST [4].

Table 3: The Main Strength Characteristics of Concrete

Количество испытанных кубов (штук)	Размер стороны кубов (см)	Серия	Sample Code	Concrete characteristics			
				Average cubic strength (MPa)	Average Prism Strength (MPa)	Axial Tensile Strength (MPa)	Modulus of elasticity (MPa)
				$\overline{R}$	$\overline{R}_b$	$\overline{R}_{bt}$	E_b
24	15±0,15	I	BT	31,7	23,4	1,825	30400
			BT 30-0	35,7	26,2	1,942	31200
			BT 60-0	28,6	21,2	1,726	29100
			BT 90-0	28,0	20,8	1,706	28950
			BT 30-5	35,7	26,2	1,942	31200
			BT 60-5	28,6	21,2	1,726	29100
			BT 90-5	28,0	20,8	1,706	28950

2.3 Prototyping

Design grade concrete for prototypes was adopted B30.

To prepare the concrete mixture was used:

- Portland cement of Karachay-Cherkess plant M300;
- crushed stone with a particle size of 5-20 mm;
- river sand of the Ust-Dzhegutinsky quarry with a density of 2.68 t / m3.
- The composition of concrete was adopted as follows: C: S: C = 1.3: 1: 3.6 at W / C = 0.422.
- The consumption of materials per 1 m3 of concrete mixture amounted to:
- cement activity M300 - 486 kg;
- crushed stone - 1340 kg;
- quartz river sand - 372 kg;
- water - 205 l.

Prototypes were made simultaneously in six formwork forms. For each sample, knitted frames were made, the clamps of which were attached to the longitudinal reinforcement with a knitting wire. To measure the deformation of the reinforcement during the test, strain gauges with a base of 20 mm were glued to the longitudinal and transverse rods. The locations of the strain gauge stickers were pre-cleaned and degreased.

After that, BF-12 glue was applied, which does not require heat treatment for polymerization. Then the strain gauges were glued with a light touch.

Special attention was paid to the arrangement of waterproofing of strain gauges, as their humidification could cause false strain effects and lead to inadequate results. As a waterproofing coating, ED-6 epoxy resin glue was used with the addition of a hardener. Before applying the waterproofing, the mixture was thoroughly mixed and applied to the surface of strain gauges for several minutes. To the strain-resistor antennae, the connecting wires were soldered, with the help of which they were connected to the automatic deformation meter of AID - 4 m. Soldering places of the mustache to connecting wires were isolated by an insulating tape and attached to the armature. After that, a waterproofing coating made of epoxy resin-based adhesive was made of the soldering points of the mustache to the connecting wires.

Concreting of the test samples was carried out two days after the application of the waterproofing coating of strain gauges. Before concreting, the inner part of the formwork was lubricated with machine oil. Then, knitted frames of prototypes were laid into the formwork. The formwork had dimensions of 150x220x2000 mm and 150x270x2000 mm.

The concrete mixture was prepared in a concrete mixer. From each mix of concrete mixture, two specimens of the same type were produced, but different in height from the version and six standard concrete cubes were concreted separately. From the same mix, six standard cubes were hammered in the concreting of these samples. The concrete mixture was compacted using deep vibrators. The open surface of the prototypes was smoothed out by a special wedge-like device. In 4-5 hours after concreting the samples were covered with wet sawdust and polyethylene film.

For 7 days after concreting, the prototypes were stripped off. On the 14th day after concreting the concrete surface of the samples was cleaned and degreased at the places of strain-resistor stickers. By the scheme of testing, the sticker of strain-resistors with the base of 50 mm on the concrete surface of the experimental beams was made.

2.4 Test Set-up of the Samples on the Effect of Pure Torsion

The test bench is a lever-rope system that allows loading on clean torsion, as well as on joint action of bending and torsion. The main elements of the experimental stand are a lever (made of channeled No. 16) equipped with a rope, a ring grip with support consoles and a grip with a circular disc (figure 2).

For torsional testing, the gripper and disc are mounted on a support frame. One end of the prototype is wound into the disc gripper and the other end into the support bracket gripper. One end of the flexible cable is wound into the disc gripper and fixed, and the other end of the cable is fixed to the test bench lever. When one end of the arm is loaded, the rope is pulled down and creates torque.

When testing samples for pure torsional action, the load is controlled from one side by the weight of the weights installed on the platform of the lever-rope system. On the other hand, the load acting on the prototype is controlled by the readings of a pre-tariffed dynamometer.

General view of the test bench is shown in figure 2

Figure 2: Installation and Measuring Equipment for Testing of Prototypes for Pure Torsional Action.

2.5 Testing Methodology of Prototypes on the Effect of Pure Torsion

By the set task of experimental research to receive the necessary reliable information about the stress-strain state of the beams, the tests of the prototypes for the effect of pure torsion were carried out.

Testing of the prototypes for the effect of pure torsion was carried out with the help of the installation as shown in figure 2. The action of pure torsion was tested on 7 beams, including one control beam of solid rectangular section.

The force on the prototype was created by the application of weights on the site, suspended on the lever (from the channel), which is connected to the rotating disc using a cable. As the load on the site increases, the lever drops down and pulls the rope by the co-failure, causing the disc to rotate. This creates a torque. The values - the load produced in this way is controlled by a certified dynamometer.

Wire strain gauges with a base of 20 mm and 50 mm, respectively, were used as primary transducers for measuring rebar and concrete deformations. The gauge of relative deformations of reinforcement and concrete was the device AID-4M with an automatic counterbalance device at measurement with the price of division 10-5 in the complete set with the switch.

The prototypes were loaded in steps that represented approximately 10% of the estimated ultimate destructive load (0.1·Pu). At the initial stage of loading (the first two stages) and the stages exceeding 0,85·Pu, the load value at the stage decreased to 0,05·Pu. At each stage, the sample was maintained for 10-15 minutes under load. Also, concrete and reinforcement deformations are measured, as well as deflections and cracks are fixed.

3. RESULTS

3.1 Concrete Deformation

In all prototypes, concrete deformations were evaluated based on the results of processing the readings of strain gages glued on all four faces of the beams. Strain gages with a base of 50 mm were located in the area of the hole length (300, 600 and 900 mm). To measure the deformation of concrete in the direction of action of the main compressive and tensile stresses, strain gages were glued along with the faces at a calculated theoretical angle of inclination to the plane of the cross-section (≈45^o).

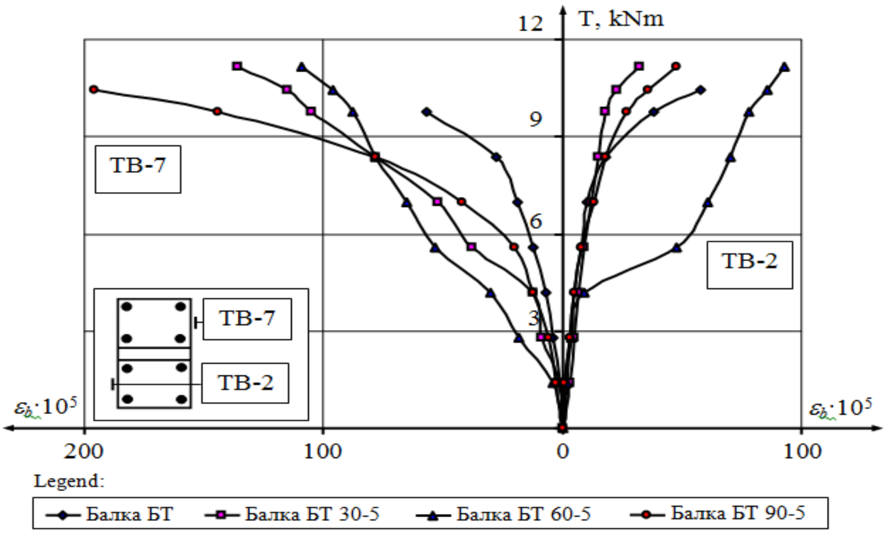

Figure 3: The Graph of Deformation of Concrete Beams During Torsion.

An analysis of these diagrams shows that before the formation of cracks, concrete deformations are insignificant and have a straightforward developmental character. Significant deformations of concrete are observed after the formation of cracks, which are non-linear.

The concrete deformations of the experimental beams of the series in the stage of the preceding destructive were (110 ... 180) · 10-5.

An intensive increase in concrete deformations has been observed since the onset of plastic deformations in reinforcement. Such concrete deformations occur at loads of (0.75 ... 0.85) *T*.

3.2 Deformation of Longitudinal Reinforcement

The deformations of the longitudinal reinforcement were recorded at each stage of loading using strain gauges glued to the longitudinal reinforcement in the zone of the length of the hole (figure 4).

In figure 4, the diagrams of deformation of longitudinal reinforcement during loading are shown. In constructing these diagrams, the averaged strain data of symmetrically positioned longitudinal reinforcement obtained from the readings of strain gauges, were used.

The analysis of the graphs shows that before the formation of cracks, the deformations of the longitudinal reinforcement are insignificant and develop according to a linear law. After the formation of cracks, there is a more noticeable development of deformations in the longitudinal arm round, which are nonlinear.

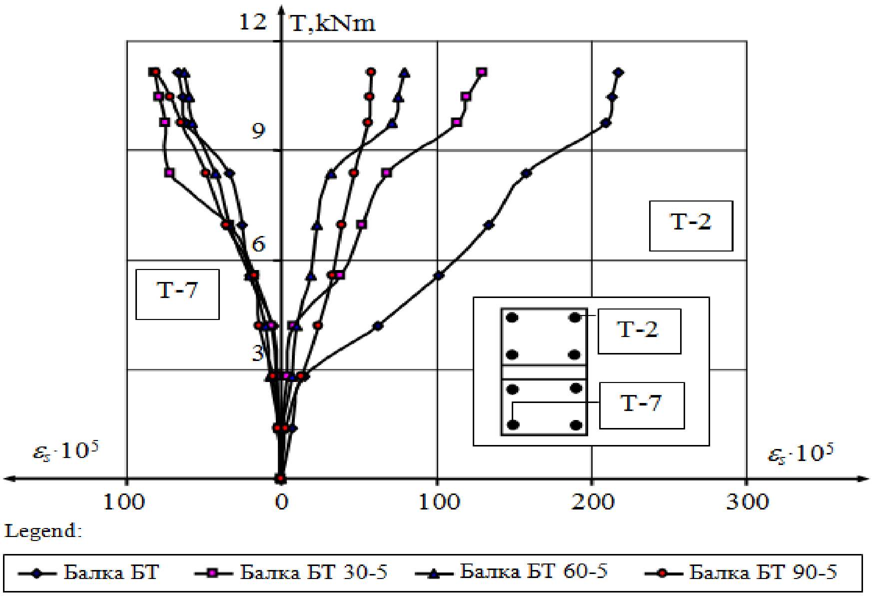

Figure 4: The Strain Profile of the Longitudinal Reinforcement of the Series with Pure Torsion.

The deformations of the longitudinal reinforcement in the stage preceding the fracture amounted to (60 ... 320) в10-5 in different experimental samples. The most intensive development of deformations of the longitudinal reinforcement of beams is observed after the formation of cracks.

3.3 Deformation of Transverse Reinforcement

The deformations of the transverse reinforcement were recorded using eight strain gauges glued on the horizontal and vertical sections of the transverse reinforcement made in the form of closed clamps. When constructing strain diagrams of transverse reinforcement, averaged data were used.

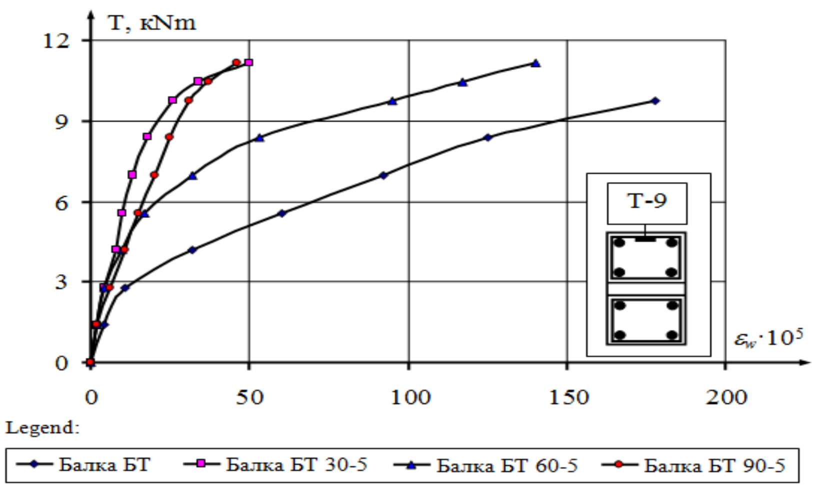

Figure 5: Scheme of Deformations of Transverse Reinforcement of a Series with Pure Torsion.

An analysis of the diagrams shows that before the formation of cracks, the change in the deformation of the transverse reinforcement occurs according to a linear law, and after the formation of cracks, an intensive increase in the strain of the clamps and the slope of the graphs is observed, starting with a load of (0.38 ... 0.5) *T*.

In the beams of the first group of series, I (BT 30-0, BT 60-0, BT 90-0) with a hole height of 5 mm, the nature of the development of deformations of the transverse reinforcement is practically the same.

The ultimate strains of the transverse reinforcement of the prototypes were (100 ... 250) · 10-5.

Tangible plastic deformations in the transverse reinforcement are observed at a load close to 0.9□*T*.

Tangible plastic deformations in the transverse reinforcement are observed at a load close to 0.9□TAt the time of failure, as shown by measurements, the entire transverse reinforcement turns out to be stretched, and the deformations of the horizontal and vertical sections of the branches of the clamps were approximately the same.

3.4 Twist Angles

Diagrams of the dependence of the twist angle on torque are shown in figure 6

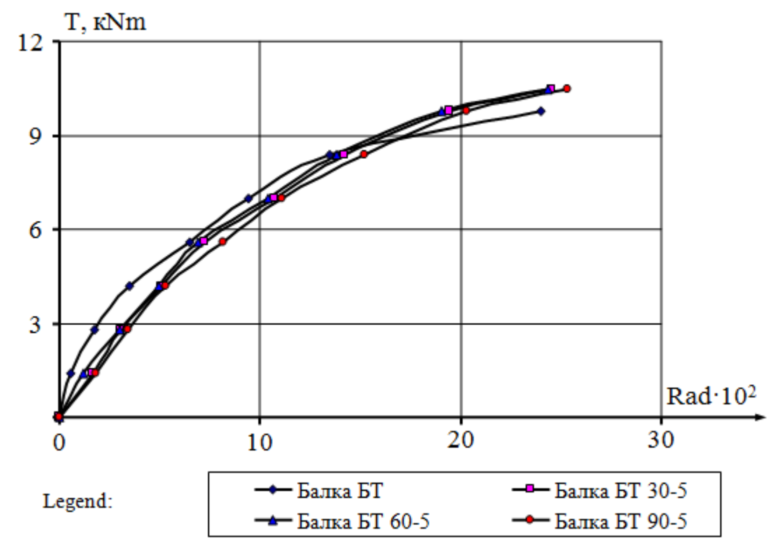

Figure 6: Changing the Angle of Twist of the Beams During Torsion.

In these diagrams of the dependence "Torque-twist angle", three characteristic sections can be distinguished:from the beginning of loading to the formation of cracks; after the formation of cracks in the zone of elastic deformation of the longitudinal and transverse reinforcement; from the moment of noticeable inelastic deformations to fracture of the samples.

Of greatest interest is the plot of the diagrams, which reflects the second stage of beam deformation - from the moment of crack formation to the beginning of plastic deformation of the reinforcement. At the time of the appearance of cracks in the diagrams, a break in the graph is noted, which characterizes a sharp decrease in the stiffness of the beams due to the formation and development of cracks.

As can be seen from the graph, the change in the twist angles in the initial stages of loading occurs uniformly according to a linear law. After the formation of cracks, an intensive increase in the twist angles and the slope of the torque-twist angle dependency diagrams are observed.

A comparison of the deformation diagrams of the longitudinal and transverse reinforcement with the graphs of the change in the twist angles of the prototypes shows that the nature of the change in the twist angles strictly corresponds to the change in the strains in the longitudinal and transverse reinforcement.

3.5 Beam Deflections

The deflections of the test beams were measured using deflection meters. Using the averaged measurement results, “M - f” dependency graphs were constructed, On these graphs, three characteristic areas can be distinguished: from the beginning of loading the prototype to the appearance of the first crack; after the formation of cracks and before the appearance of inelastic deformations in the longitudinal or transverse reinforcement; from the appearance of noticeable plastic deformations in the reinforcement of beams and to failure.

Diagrams of the dependence of the twist angle on torque are shown in figure 7

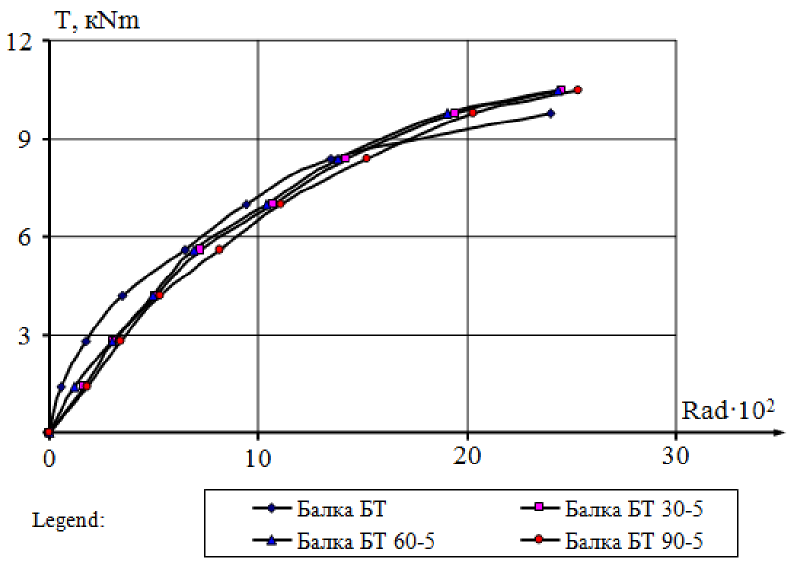

Figure 7: Change in the Twist Angle of the I-Series Beams During Torsion.

An analysis of the graph shows that before the appearance of cracks, the deflections develop linearly, and after the formation of cracks, the intensive development of deflections is observed.

4. DISCUSSIONS

4.1 Strength Analysis of Torsion Beams

In a study [10] by D. K. Kasaev, a new approach was proposed to solve the problem of assessing the strength of reinforced concrete in torsion. As a result of the tests, the values of the experimental destructive torsional and bending moments of rectangular beams with through-holes during torsion were established.

Three options for calculating the torque value T were considered:

Option 1 - determination of bearing capacity as for a continuous beam by external dimensions, i.e., by the formula

$$T = \frac{0,8}{1+2\cdot\xi_{\text{т}}} b_o \cdot h_s \cdot q \cdot (1+\varphi) \cdot \sqrt{\frac{1+\varphi^2}{1+\varphi^4}}\,, \qquad (1)$$

where $\varphi = q_w / q_s$; $\xi_{\text{т}} = \sqrt{\xi_s^2 + \xi_w^2}$; $\xi_s = \frac{\sigma_s \cdot A_{s.tot}}{R_b \cdot b \cdot h}$; $\xi_w = \frac{2 \cdot \sigma_w \cdot a_w}{R_b \cdot b \cdot S}$;

$q_s = \frac{\sigma_s \cdot A_{s.tot}}{2 \cdot (h_s + b_s)}$; $q_w = \frac{\sigma_w \cdot a_w}{S}$; $q = \sqrt{q_s^2 + q_w^2}$.

Option 2 - determination of the bearing capacity of one branch with the subsequent doubling of the result (figure 8) using the formulas

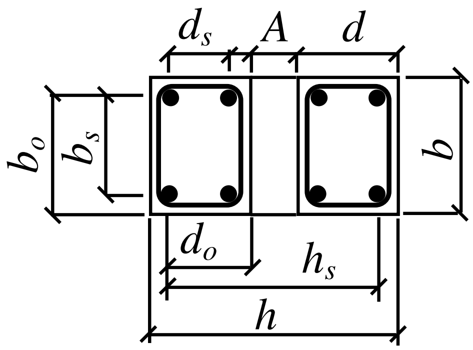

Figure 8: The Calculated Cross-Section of the Experimental Beams.

$$T_{\text{v}} = \frac{0{,}8}{1 + 2 \cdot \xi_{\text{т}}} d_o \cdot b_s \cdot q \cdot (1 + \varphi) \cdot \sqrt{\frac{1 + \varphi^2}{1 + \varphi^4}} , \tag{2}$$

where $\varphi = q_w / q_s$; $\xi_{\text{т}} = \sqrt{\xi_s^2 + \xi_w^2}$; $\xi_s = \frac{\sigma_s \cdot A_{s.tot.\text{v}}}{R_b \cdot d \cdot b}$; $\xi_w = \frac{2 \cdot \sigma_w \cdot a_w}{R_b \cdot d \cdot S}$;

$q_s = \frac{\sigma_s \cdot A_{s.tot.\text{v}}}{2 \cdot (b_s + d_s)}$; $q_w = \frac{\sigma_w \cdot a_w}{S}$; $q = \sqrt{q_s^2 + q_w^2}$.

The total torque is determined by the formula

$$T = 2 \cdot T_{\text{v}} ; \tag{3}$$

Option 3 - calculation of the bearing capacity as for a continuous beam minus the dimensions of the hole, i.e., by the formula

$$T = \frac{0{,}8}{1 + 2 \cdot \xi_{\text{т}}} b_o \cdot 2 \cdot d_s \cdot q \cdot (1 + \varphi) \cdot \sqrt{\frac{1 + \varphi^2}{1 + \varphi^4}} , \tag{4}$$

where $\varphi = q_w / q_s$; $\xi_{\text{т}} = \sqrt{\xi_s^2 + \xi_w^2}$; $\xi_s = \frac{\sigma_s \cdot A_{s.tot}}{R_b \cdot b \cdot 2d}$; $\xi_w = \frac{2 \cdot \sigma_w \cdot a_w}{R_b \cdot b \cdot S}$;

$q_s = \frac{\sigma_s \cdot A_{s.tot}}{2(2d_s + b_s)}$; $q_w = \frac{\sigma_w \cdot a_w}{S}$; $q = \sqrt{q_s^2 + q_w^2}$.

4.2 Strength Analysis of Experimental and Theoretical Results Torsion Beams

To identify the most acceptable approach for calculating the load-bearing capacity of rectangular beams with through holes subjected to torsion, calculations were carried out according to the three above options.

The results of these calculations and their comparison with experimental data are given in the tables. 4, 5, 6.

Table 4: Comparison of Experimental and Theoretical Torques According to the First Option (f. 1)

№ p/p	Cipher Beams	b, sm	h, sm	b_s, sm	h_s, sm	b_o, sm	S, sm	$\sigma_w a_w$, кН	$\sigma_s A_{s,tot}$, кН	R_b, МПа	T^{exp}, кНсм	T, kNsm	T^{exp}/T
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1.	BT	15,0	22,0	10,5	17,5	12,8	5	9,3	506	23,4	975	874	1,12
2.	BT 30-0	14,8	22,0	10,4	17,5	12,6	5	9,3	506	26,2	956	912	1,05
3.	BT 60-0	15,0	21,8	10,6	17,3	12,8	5	9,3	506	21,2	975	813	1,20
4.	BT 90-0	15,1	21,9	10,7	17,4	12,9	5	9,3	506	20,8	929	816	1,14
5.	BT 30-5	14,9	27,0	10,5	22,5	12,7	5	9,3	506	26,2	1115	1163	0,96
6.	BT 60-5	14,9	26,9	10,5	22,4	12,7	5	9,3	506	21,2	1115	1037	1,07
7.	BT 90-5	15,0	26,9	10,6	22,4	12,8	5	9,3	506	20,8	1045	1036	1,01

The ratio of the experimental value of the torque to the theoretical value obtained by the formula (1) for the experimental sample - the standard BT of a solid rectangular section was 1, 12.

Table 5: Comparison of Experimental and Theoretical Torques According to the Second Option (f.2)

№ п/п	Cipher Beams	b, sm	h, sm	d, sm	b_s, sm	d_s, sm	d_o, sm	S, sm	$\sigma_w a_w$, кН	$\sigma_s A_{s,tot}$, кН	R_b, МПа	T^{exp}, кНсм	T, kNsm	T^{exp}/T
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1.	BT 30-0	14,8	22,0	11,1	10,4	6,6	8,9	5	9,3	253	26,2	956	663	1,44
2.	BT 60-0	15,0	21,8	11,0	10,6	6,5	8,8	5	9,3	253	21,2	975	591	1,65
3.	BT 90-0	15,1	21,9	11,0	10,7	6,5	8,8	5	9,3	253	20,8	929	590	1,58
4.	BT 30-5	14,9	27,0	11,1	10,5	6,6	8,9	5	9,3	253	26,2	1115	669	1,67
5.	BT 60-5	14,9	26,9	11,0	10,5	6,5	8,8	5	9,3	253	21,2	1115	585	1,90
6.	BT 90-5	15,0	26,9	11,0	10,6	6,5	8,8	5	9,3	253	20,8	1045	584	1,79

Table 6: Comparison of Experimental and Theoretical Torques According to the Third Option (f. 4)

№ п/п	Cipher Beams	b, sm	h, sm	b_s , sm	$2d_s$, sm	b_o, sm	S, sm	$\sigma_w a_w$, кН	$\sigma_s A_{s,tot}$, кН	R_b , МПа	T^{exp}, кНсм	T , kNsm	T^{exp}/T
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1.	BT 30-0	14,8	22,0	10,4	17,5	12,6	5	9,3	506	26,2	956	916	1,04
2.	BT 60-0	15,0	21,8	10,6	17,3	12,8	5	9,3	506	21,2	975	818	1,19
3.	BT 90-0	15,1	21,9	10,7	17,4	12,9	5	9,3	506	20,8	929	818	1,14
4.	BT 30-5	14,9	27,0	10,5	17,5	12,7	5	9,3	506	26,2	1115	924	1,21
5.	BT 60-5	14,9	26,9	10,5	17,4	12,7	5	9,3	506	21,2	1115	813	1,37
6.	BT 90-5	15,0	26,9	10,6	17,4	12,8	5	9,3	506,2	20,8	1045	811	1,29

A comparative analysis of the experimental and calculated results for the considered options allows us to draw the following conclusions:

- the average value of the ratio of the experimental moments to the calculated values in the calculations according to the first option (table 4) was 1.07 with the minimum and maximum ratios of 0.96 and 1.2, respectively;
- calculations according to the second option (table 5) reveals an underestimation of the bearing capacity by an average of 67%;
- calculations according to the third option (table 6) are as follows:
  - for beams with a hole height of 5 mm (BT 30-0, BT 60-0, BT 90-0), the ratio of the experimental moment to the calculated one averaged 1.12 with minimum and maximum deviations of 1.04 and 1.19 respectively;
  - for beams with a hole height of 50 mm (BT 30-5, BT 60-5, BT 90-5) these indicators were as follows: with an average value of 1.29, a minimum of 1.21, a maximum of 1.37.

The average value of the ratio of the experimental moments to the calculated values for all six beams was 1.21 with the minimum and maximum ratios of 1.04 and 1.37, respectively.

In general, the best convergence of the experimental and calculated results is observed when calculating according to the first option, when the calculation is carried out as for a solid rectangular beam. If we compare the results obtained for beams BT 30-0, BT 60-0, BT 90-0, in which there was a gap of 5 mm wide, then the convergence of the experiment with the calculation is better according to the third variant. For samples with a hole width of 50 mm, its ratio to the working height of the beam was 0.25. As this parameter increases, the effect of the hole may increase. Considering this and taking a cautious approach, we can conclude that the third option of calculation should be considered the most acceptable, that is, adopt the formula (4).

It should be noted that the influence of the length of the hole on the bearing capacity of samples with through-holes during torsion was not detected.

5. CONCLUSIONS

- The studies of reinforced concrete beams with through holes for torsion showed that the scheme of their work is the same as for elements of a solid rectangular section.
- As a result of experimental studies, a set of new experimental data was obtained on the strength of one beam of a continuous section and beams with through-holes during torsion. This set includes data on the moments of crack formation, the nature of the development of cracks, deformations of concrete, deformations of longitudinal and transverse reinforcement, twisting angles and deflections, as well as the bearing capacity of the beams during torsion.
- It was found that a separate application of torque in one case increases, and the other reduces the twist angles of the beams with through holes. Moreover, an increase is observed in prototypes with a hole height of 50 mm, and a decrease in beams with a hole height of 5 mm.
- The influence of the length of the hole on the bearing capacity of samples with through-holes during torsion was not detected.

The proposed recommendations for calculating the strength and designing reinforced concrete elements of rectangular cross-section with through holes in the presence of torsion allow rational use of the strongest resources of concrete and steel and can be used in the preparation of regulatory documents.

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